PHYSICS AND ENGINEERING DESIGN OF ELECTRON CYCLOTRON CURRENT DRIVE SYSTEM FOR JA DEMO

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This paper presents design activities for electron cyclotron current drive (ECCD) for the JA DEMO tokamak from the physics and engineering viewpoints. ECCD is expected to be a primary current drive method regarding its advantage in radiation circumstances, and we aim to establish the design for full current drive by ECCD. Major topics for this target are as follows: (i) Analysis of ECCD physics for current drive efficiency improvement shows that an upper-side injection can produce 0.05 A/W of current drive efficiency by avoiding absorption at second harmonic resonance. (ii) A conceptual design of the 100 MW class RF power source, which is necessary for the full current drive, represents that the RF power plant needs a 50 m x 100 m scale building and > 200 m range transmission lines. (iii) A launcher concept that utilizes remote steering technology is evaluated, and the extended operating range of 8-19 deg oblique injection is represented.

1. Introduction

JA DEMO is a tokamak fusion reactor aiming to demonstrate steady and stable electric power generation on a power plant scale, producing several hundreds of MW of electric power. The JA DEMO requires a design that can achieve reasonable stability to operate as a power plant. Electron cyclotron heating and current drive (ECH/CD) system is one of the major components of the JA DEMO, and it is expected to play an essential role in its plasma operation scenario. Since the EC system has the advantage of operating in radiation circumstances, ECCD is expected to be a primary current drive method for the JA DEMO. This paper reports recent results from design activities of the ECH/CD system for the JA DEMO, which are divided into physics and engineering approaches.

2. Physical Analysis for ECCD Efficiency Improvement

Physical analysis of ECCD aims to improve the current drive efficiency. Since the power consumption by low efficient ECCD operation reduces the output electric power from the plant, improving the current drive efficiency is highly demanded. To find out the methods to improve the current drive efficiency, following analysis were performed: a survey of the injection port, optimal injection condition search with non-linear effect, and multi-frequency heating. For these approaches, several analysis codes, namely TRAVIS, PARADE, and TASK, are utilized.

TRAVIS[1] and PARADE[2] codes have been applied to the JA DEMO configuration, and find that if the fundamental EC wave is injected from the outside equatorial plane (Fig.1 (a)), unexpected absorption due to second harmonic resonance will occur in the edge plasma area, resulting in the broadening of the power deposition profile. A launch from the upper side of the torus (Fig.1 (b)) has been studied to resolve this problem. The results show that the second harmonic resonance can be avoided, and the power deposition profile remains localized in the equatorial plane.

FIGURE 1. Example of RF power injection ray trace for high efficient current drive by TRAVIS code: (a) launch from equatorial plane: (b) launch from upper side.
core region without decreasing current drive efficiency. The current drive efficiency was estimated as 0.05 A/W at this configuration.

A dual-frequency injection method is also analyzed to improve the current drive efficiency. Acceleration of high-speed electrons is effective since deceleration due to Coulomb collision with ions is small. However, the drive efficiency is low since the fundamental harmonic electron cyclotron resonance region in the velocity space is located in an area with a relatively slow perpendicular velocity. Therefore the dual wave scheme where bulk electrons are accelerated by the fundamental cyclotron resonance and further accelerated by the second harmonic cyclotron resonance has been considered. Since the usual forward second harmonic resonance is away from the fundamental resonance in velocity space, the use of backward second harmonic resonance, which can be closer to the fundamental resonance in velocity space, is also considered. Preliminary analysis using the TASK code shows that the current drive efficiency can be enhanced by this method.

3. Conceptual Design of RF Power Plant

In parallel with the JA DEMO architecture design, the conceptual design of the ECH/CD system plant for JA DEMO is underway. As a preliminary plant specification, the power level is assumed to be 100 MW class with a frequency range > 200 GHz. This conceptual design aims to clarify the engineering development target in the next step of JA DEMO development, planned to start in 2027.

The RF power source of the ECH/CD system consists of gyrotrons, high-voltage power supplies, transmission systems, and various auxiliaries. For 100 MW class power generation, the RF power plant becomes a cluster of 1 MW class gyrotrons. Since gyrotron utilizes cyclotron resonance maser reaction, which requires a strong magnetic field, interference of gyrotron magnet and tokamak magnetic field harms gyrotron operation [3]. Hence the location of the RF power plant in the JA DEMO site shall be 120 m far from the tokamak center where JA DEMO the tokamak magnetic field becomes lower than 0.5 mT. Then RF power is delivered to tokamak with transmission lines (TL), and the length of TL becomes longer than 200 m. Interference of nearby gyrotron magnets is another design constraint of the component layout of the RF power plant. In the ITER case, the minimum distance between gyrotrons is 5 m. This requirement determines the scale of the RF plant building as 50 m x 100 m, including the location for the power supply system.

4. Conceptual Launcher Design for ECCD

Basic research of EC launcher technology is another primary scope of design activity. Since the launcher system for the JA DEMO locates in a very severe radiation environment, front mirror steering technology is complicated to apply in the JA DEMO. The remote steering launcher technology is expected to be promising for the JA DEMO. An RF transmission simulation of remote steering and phase controlling launcher with 4 x 4 waveguides represents well controllability of focused beam position in a tokamak plasma.

A large oblique angle injection is demanded ECCD operation, and the possibility of a large oblique angle injection is examined by simulation and low power experiment. Remote steering can typically control incident angles between 0-12 degrees[4]. An extended operational range (8-19 degrees) has been proposed and confirmed at the low-power test. The other extended operating range of the remote steering antenna will be surveyed for the JA DEMO application.

As an integrated design of an upper injection launcher in JA DEMO tokamak, a launcher port space in a tokamak vacuum vessel is evaluated according to the physical requirement for ECCD operation. The location of the launcher port is determined by avoiding interference with the toroidal field coil support structure, as shown in Fig.2. The port size and angle of port direction are limited to prevent interference with the poloidal field coil and vacuum vessel surrounding components. Design works on a remote steering mechanism and a fixed quasi-optical mirror is in progress to provide an RF beam with a proper injection angle.

FIGURE 2. Example of launcher port location for upper injection in tokamak vacuum vessel.
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